(NASA-CR-154663) CONSUMABLES OPERATIONAL LIMITS OF AN EXTENDED DURATION FLIGHT ON MISSION AS-204 (Bellcomm, Inc.) 13 p

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SUBJECT: Consumables Operational Limits of an Extended Duration Flight on Mission AS-204 - Case 330

DATE: January 27, 1967

FROM: S. S. Fineblum

ABSTRACT

This memorandum updates an earlier "quick-look" study of the average consumables usage required to realize an extended duration AS-204 mission.

The results were illustrated in the earlier report by superimposing a region of operation on a set of basic data which related net water usage to the total D. C. electrical power load. The bounds of this operational envelope were determined by ECS radiator performance, consumables available for power generation and thermal control and the minimum power required to achieve the mission objectives. These boundaries were expressed as average values for the total flight.

In this report, the effects of fuel cell voltage regulation and the combination of individual fuel cell water-versus-power characteristics have been considered.

The results show that an assumed 14-day flight is feasible provided that the ECS radiator performance does not degrade beyond an absorptivity of approximately 0.47 (0.34 was reported earlier, 0.2 is normal). Under conditions of drifting flight, the total permissible electrical load without water boiling is approximately 1350 watts with undegraded radiators. If the SM RCS is used to control attitude to optimize radiator heat rejection, this power can be increased to 1800 watts.

Graphical operational envelopes are also presented for one, two, and three fuel cell configurations.

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MEMORANDUM FOR FILE

1.0 Introduction

This report updates an earlier memorandum[1] which provided a "quick look" at the requirement for managing consumables on the AS-204 mission for an extended duration flight. The bases for analysis are summarized to minimize the need to refer to the initial report. In this updated study, however, the effects of operating with three, two, and one fuel cell configurations are considered.

The analysis is illustrated on the attached figures as an envelope which is bounded by average rates of consumable expenditures which must be achieved to accomplish the assumed mission duration objective.

Specifically, this updating study takes into consideration the variation of D. C. bus voltage with load current and the slight variations of the water production versus power-dissipated in-the-CM characteristics for three, two, and one fuel cell configurations. Taking these differences into account allows more accurate prediction of net water consumption with degraded radiators as reported in the earlier memorandum. In addition, this study includes consideration of the power levels that can be sustained with no water boiling.

As in the earlier memorandum, the analysis is concerned with consumables which are currently considered to be critical constraints to mission duration (i.e., cryogenic hydrogen, water and SM RCS propellant). Command Module RCS and Service Propulsion System propellants, spacecraft cryogenic oxygen, batteries and other life support consumables (e.g., food, LiOH cartridges, etc.), are not considered to be critical constraints on mission length. Accordingly, no attempt has been made to incorporate these consumables into the study.

The basic data and most of the supplementary data have been obtained from the Mission Modular Data Book[2] prepared by North American Aviation. An electrical power prediction from MSC[3]

[redacted]

was used in that instance where the information contained in the NAA Data Book was incomplete. The thermal balance is based on the portion of electrical power consumed in the Command Module, as well as assumed average metabolic loads (1500 BTU/hr) and CM heat leaks (-600 BTU/hr).

2.0 Consumables Expenditures Envelope

For purposes of illustration, a 14-day mission is assumed. Missions of shorter duration will allow more latitude for operation (i.e., larger envelopes).

The bounds of the envelope shown on the attached figures are determined by the following six constraints:

1. Water consumption for evaporative cooling.
2. Minimum average power level to satisfy the AS-204 mission objectives.
3. Maximum average power level permissible for extended duration.
4. ECS radiator performance.
5. SM RCS propellant available for attitude control.
6. Minimum voltage requirements.

These are discussed in the following sections.

2.1 Water Consumption for Evaporative Cooling (Lower Boundary)

Net water to storage was defined in Reference 1 as the hourly rate difference between the water being generated and the water consumed during flight.

The critical determinants were, (a) the water produced by the fuel cells, (b) the water used in the evaporative heat exchangers, and (c) water stored on board at launch. When the water consumption rate exceeds the generation rate, the additional water must come from stored reserves.

For 202.5 lbs of usable water in CM and SM storage tanks at launch (maximum CM and SM storage capacity is 204 lbs) and a mission length of 330 hours, the maximum average net consumption rate of water may not exceed production by more than 0.61 lb/hr. This is the lower boundary of the operating envelope as shown in Figure I.

2.2 Minimum Average Power Level (Left-hand Boundary)

The minimum average power level is estimated at 1710 watts[(3)]* which is attainable only if the drifting flight, powered-down mode is adopted. There are, of course, peak electrical loads considerably above the 1710-watt figure as well as long periods of slightly lower demand.

2.3 Maximum Average Power Level (Right-hand Boundary)

Maximum average power level attainable is 1800 watts. This level was based in the earlier report on the total amount of hydrogen available for power generation during flight, approximately 56 lbs, assuming 100% loading.

2.4 ECS Radiator Performance (Sloping Boundary)

As stated in the earlier memo, ECS radiator performance is a function of spacecraft attitude (i.e., orientation to the sun, earth, and deep space as heat sources or sinks) and the thermal characteristics of the coating (i.e., e = emissivity and α = absorptivity). The absorptivity of a clean radiator is 0.2. Some test data indicate that thermal coatings may be degraded by boost heating, retro-rocket exhaust, or by RCS plume impingement. As the radiator coatings degrade, they are less effective in rejecting heat and the system thermal balance will require more and more water boiling. The fixed supply of water limits, therefore, the total heat that can be rejected and thus limits maximum permissible electrical power load in the CM.

The maximum power level with water boiler operation decreases with radiator degradation from 1800 watts with a radiator with α between 0.2 and 0.4, down to 1710 watts with a more degraded radiator, $\alpha \approx .47$, as shown in Figure I.

An increase of α from 0.2 to 0.5 decreases the heat that is rejected from the radiators and, therefore, decreases the power level that could be thermally balanced without water boiling from approximately 1350 watts down to approximately 1000 watts. The results of this study indicate that if this absorptivity is, however, not degraded beyond approximately 0.47 (see Figure I), it will be feasible to operate with three fuel cells for 14 days provided that average power is maintained at the minimum average power level of 1710 watts (drifting flight, powered down). This is the corner formed by maximum allowable net water consumption and the minimum average power.

*A load of 1554 watts was used in the earlier study.

2.5 SM RCS Propellant

As noted in the earlier memo, current analyses indicate that a 14-day flight is feasible with fully-loaded SM RCS tanks (790 lbs of usable propellant) with zero margin only if the drifting flight, powered-down mode is adopted so that no RCS propellant is used to establish and maintain the CSM in a favorable attitude for thermal control purposes.

At the expense of mission duration, SM RCS propellant may be expended to reduce water consumption by adopting attitude hold modes for thermal control. This decision may be necessary to compensate for excessive water boiling due to degraded radiator performance or high heat loads resulting from unfavorable attitudes which are dictated by other mission objectives. In the figures, the two upper right-hand curves show the results if the most favorable attitude is maintained. The RCS cost is about 1 to 2 lbs/hr of attitude hold. The cost is the same even if less favorable attitudes are maintained.

2.6 Electrical Power Consumption Without Water Boiler Operation

At low power levels, net water flow to storage increases linearly with the current output. This is indicated in the figure by the straight line with positive slope. The net water to storage will not be diminished by water consumption for boiling, until the thermal capacity of the radiators is exceeded. Initiation of water boiling is indicated where net-water-to-storage lines change from positive to negative slopes. No water boiling is required to the left of these points. For instance, with three fuel cells operating and a clean radiator (α = 0.2), 1350 watts may be consumed before water is evaporated for supplemental cooling. This is under conditions of drifting flight. However, if the attitude can be optimized for thermal control (to obtain a minimum of solar radiation on the radiator panels) a larger heat load can be rejected by the radiators and approximately 1800 watts may be consumed before water boiling is required.

2.7 Operation with One and Two Fuel-Cell Configuration

When only two fuel cell modules are operating, the composite voltage-vs-current and water-vs-power (dissipated in the CM) characteristics are altered. The alteration is due to the combined fuel cell impedances and the decrease in Service Module electrical power requirements for each shut-off fuel cell module (approximately 105 watts per cell). The relation of net water production to composite fuel cell output is, therefore, modified. The reduction of minimum average power as a result of eliminating the load of the "off" fuel cell module utilities is shown in Table I. As noted in Figure II, the maximum available average water consumption of 0.61 lbs/hr will be consumed by the minimum average power level of 1514 watts if the radiator degrades to $\alpha \approx 0.47$. A cleaner, brighter radiator will, of course, permit higher power levels. The permissible CM and SM power consumption with undegraded radiators and without the use of the water boiler decreases from 1350 watts (for three fuel cells) to approximately 1200 watts for two fuel cells. Hydrogen is conserved by a two fuel cell operation since the power consumed in the SM by the fuel cell pumps of the "off" module is no longer required.

With only one fuel cell operating, the output voltage is, of course, severely decreased. The elimination of the fuel cell pump loads of the two "off" fuel cell modules in the SM permits a significant decrease of minimum average total power. As noted in Figure III, this 14-day minimum average total power, now only 1272 watts, is less than the maximum permissible power of 1350 watts as determined by the minimum operational D. C. bus voltage of 26 volts.* Exceeding this maximum permissible power during peak loads would present line voltage problems. (This particular deficiency suggests the need for a review of mission rules for fuel cell failure abort criteria for the LOR mission, as well as for this mission.)

3.0 Conclusions

In order to obtain extended duration missions, careful management of consumables, particularly H_2, is necessary. An operational envelope has been developed relating electrical power, environmental control, and SM RCS propellant for attitude hold within which successful operation is possible. The effects of possible degradation of thermal coatings on the radiators has also been shown.

The limits of operation with water boiling are, (a) 1800 watts maximum average power with a clean radiator and 56 lbs of available hydrogen, (b) 1272, 1514, and 1710 watts minimum average power required to support the mission with one, two, and three fuel cells respectively, and (c) $\alpha = 0.47$ maximum permissible radiator absorptivity consistent with maximum average permissible net water consumption of 0.61 lbs/hr. The limits of operation with no water boiler are 1350 watts and 1800 watts, with drifting flight and optimum thermal attitude control respectively, with clean radiators and three fuel cells. These values are reduced with one or two fuel cells or degraded radiators.

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*Voltages less than 26 volts result in degraded operation of the SM RCS, gimbal motor control, and SCS subsystems.

Some hydrogen economy is achieved by a two fuel cell operation because power is no longer consumed by pumps in the "off" fuel cell module. One cell operation, however, cannot support a reasonable mission because of deficient system voltage during peak loads.

Suggested future efforts are:

a) A supplementary study to determine the feasibility of expending SM RCS propellant for thermal control through attitude hold based on available propellant margin as a function of time.

b) Similar analyses for unique missions or mission phases during which demand rates for consumables may be constrained by delivery or consumption rate capabilities of one or more systems (e.g., supercriticality constraints on cryogenic delivery rate, maximum water boiling capability, etc.).

c) Similar analyses for the first manned Block II mission, the Block II LOR mission, and for the LM.

d) A study to examine the desirability and feasibility of using the LM batteries to supply CSM power for aborts during the LOR mission with one and two fuel cell module failures.

e) Incorporation of latest test data for performance of radiators as such data become available.

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Attachments
References
Table I
Figures I-III

Copy to
(See next page)

Copy to
Messrs. C. H. Bolender - NASA/MO
L. E. Day - NASA/MAT
C. C. Gay - NASA/MAT
J. K. Holcomb - NASA/MAO
T. A. Keegan - NASA/MA-2
A. F. Phillips - NASA/MAT
M. L. Seccomb - NASA/MAP
J. H. Turnock - NASA/MA-4
G. C. White - NASA/MAR
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R. V. Battey - MSC/PM3
D. Bell - MSC/EP5
A. Cohen - MSC/PD4
J. W. Craig - MSC/PD4
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REFERENCES

(1) Consumables Management Required to Provide and Extended Duration Flight on Mission AS-204, Memorandum for File dated October 5, 1966, by T. A. Bottomley and S. S. Fineblum.

(2) SID 66-1177 Mission Modular Data Book - First Block I Manned Mission, NAA, dated September 1, 1966.

(3) Preliminary AS-204 Flight Plan, MSC, dated September 6, 1966.

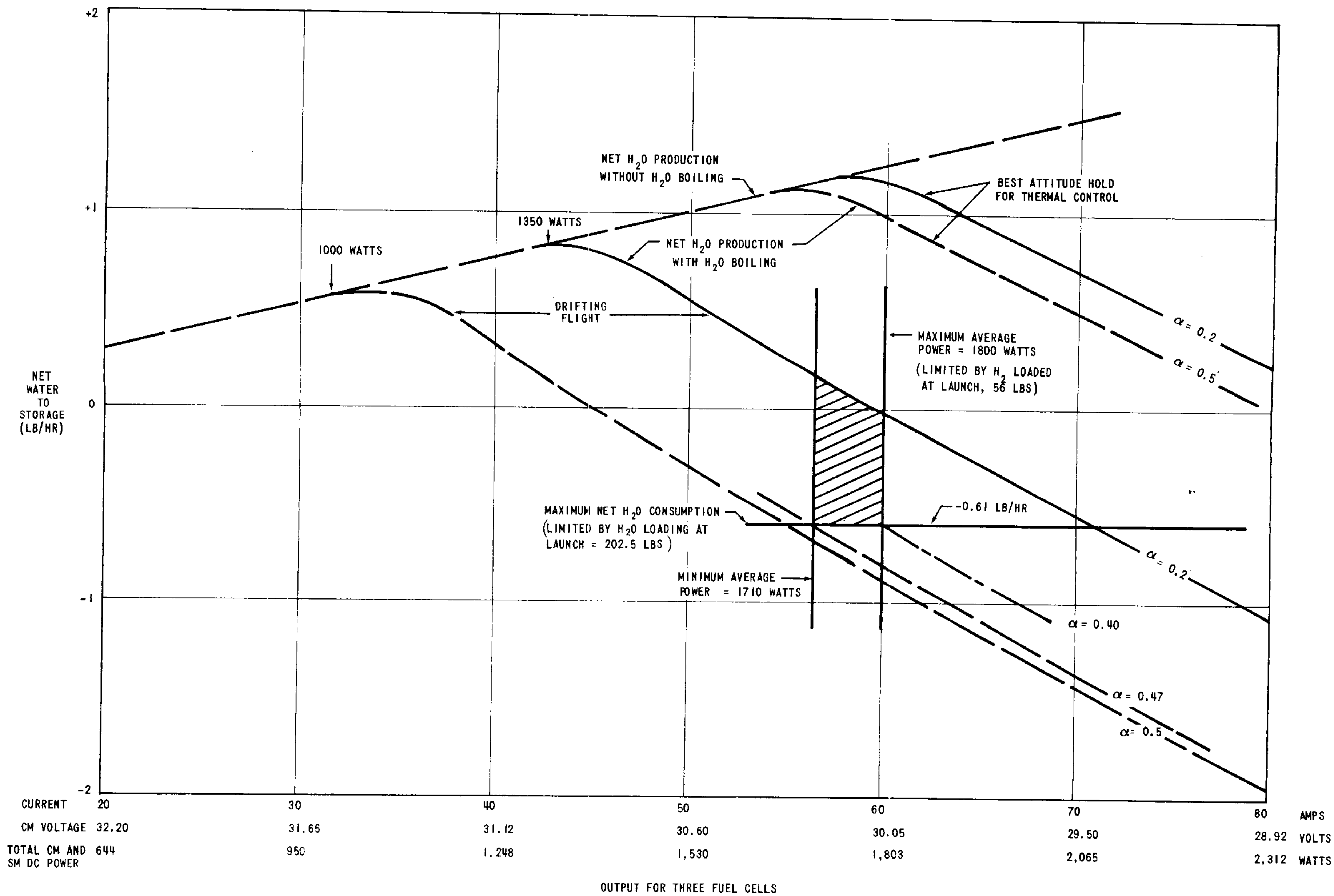
TABLE I

ELECTRICAL POWER SYSTEM LOADS FOR POWERED-DOWN DRIFTING FLIGHT

	Nominal Equipment Power AC	Nominal Equipment Power DC	Buss Voltage	Amperage AC	Amperage DC	Amperage Total	Total F/C Power
Three Fuel Cells Operating[a]	707	654	30.0	32	25	57	1710
Less First F/C Pump, etc.[a]	105						
Two Fuel Cells Operating[b]	602	654	29.1	28	24	52	1514
Less Second F/C Pump, etc.[a]	105						
One Fuel Cell Operating[c]	497	654	26.5	26	22	48	1272

Note:

(a) Data from Reference 3.
(b) Calculations from Figure 3-2 of Reference 2.
(c) Calculations from Figure 3-3 of Reference 2.

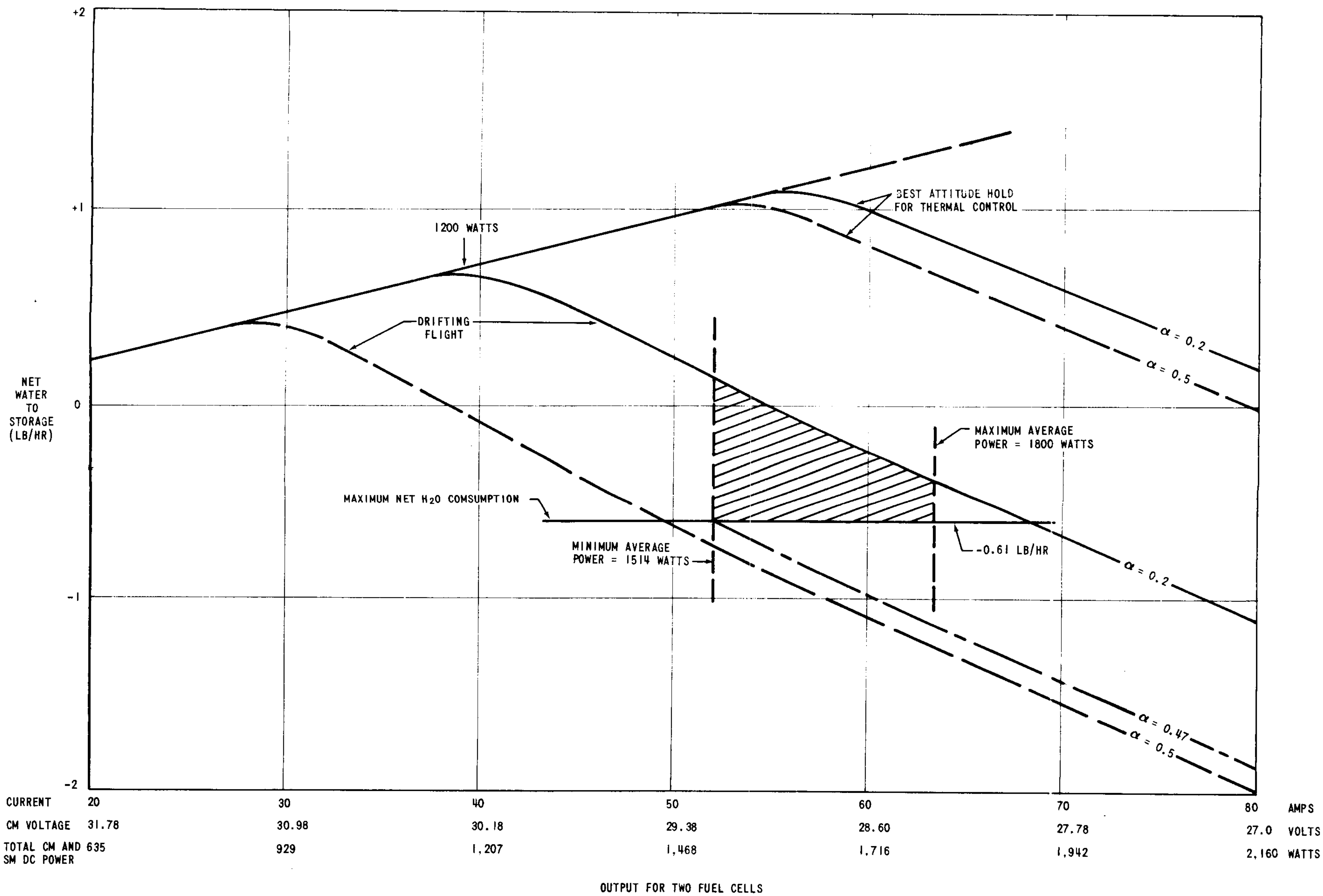


AS 204 CSM LIMITS-THREE FUEL CELLS

ASSUMED MISSION DURATION - 14 DAYS
ALL CURVES SHOW AVERAGE CONSUMPTION

FIGURE I

MAS/Bellcomm

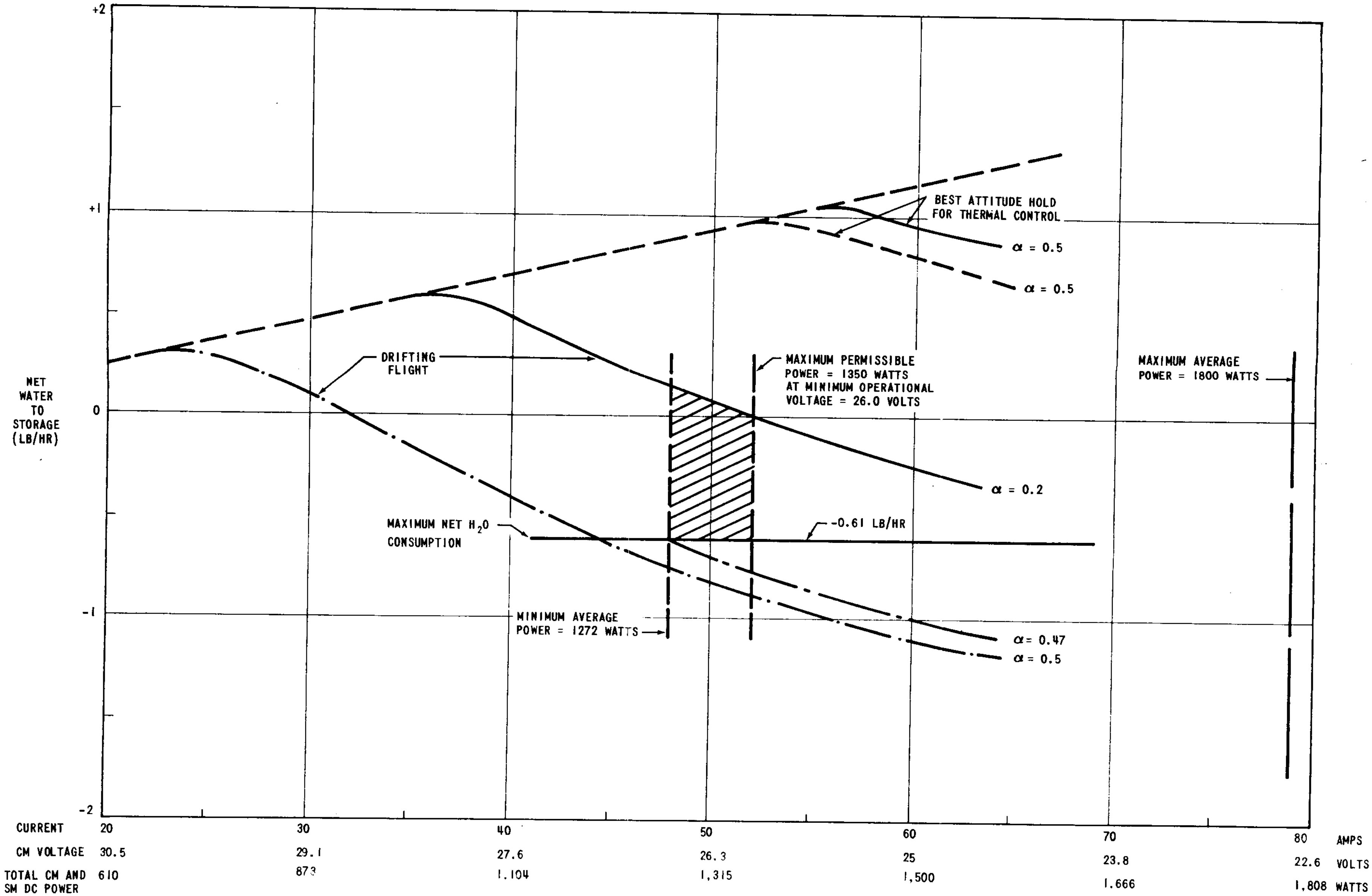


AS 204 CSM LIMITS - TWO FUEL CELLS

ASSUMED MISSION DURATION - 14 DAYS
ALL CURVES SHOW AVERAGE CONSUMPTION

FIGURE 11

MAS/Bellcomm



OUTPUT FOR ONE FUEL CELL MODULE

AS 204 CSM LIMITS-ONE FUEL CELL

ASSUMED MISSION DURATION - 14 DAYS
ALL CURVES SHOW AVERAGE CONSUMPTION

FIGURE III

MAS/Bellcomm